INSTITUTE OF PAPER CHEMISTRY
Appleton, Wisconsin

A STUDY OF FACTORS PERTAINING TO HARDWOOD PULP UTILIZATION

I. THE TEARING BEHAVIOR OF HARDWOOD-SOFTWOOD PULP BLENDS

II. SELECTED TOPICS ON THE TEARING STRENGTH OF PAPER

Project 2502

Report Three

A Progress Report

to

MEMBERS OF GROUP PROJECT 2502

February 29, 1968

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SUMMARY AND CONCLUSIONS

It was concluded that studies of the tearing strength of paper, whether of hardwoods or softwoods, have been necessarily empirical in nature because of an inadequate understanding of the mechanism of the tearing fracture process. A much better understanding of the tearing process will be needed before any quantitative analysis of tearing energy is justified. In this context, several aspects of the tearing behavior of paper were discussed which might be related to the energy of deforming the individual fibers in the tearing process.

The comparatively low tearing strength ratios of anisotropic papers relative to tensile strength ratios, elastic modulus ratios, etc., were discussed from two different points of view. First, it was suggested that the tearing process could be somewhat biaxial in nature in that energy contributions are important from fibers lying at all angles to the tearing direction. Secondly, the fact that the work required to rupture individual fibers in axial tension is not affected as much by drying tensions or shrinkages as is tensile strength, elastic modulus, or extension at rupture suggests that the lower tearing strength ratios could be related to the work of deforming the individual fibers.

The effect of relative humidity on the tearing strength of paper was discussed because it was felt that a principal factor accounting for the increased tearing energy at higher relative humidities was an increased extensibility of the fiber. It was shown that the tensile stretch and Elmendorf tearing strengths are to a first approximation linearly related if these properties are treated as averages of the machine and cross-machine direction values.

The distribution of stress within and about the fracture zone was discussed as a potential explanation of a maximum in the in-plane tearing strength. However, no direct information relative to such stress concentration effects, etc., were available.

With the help of crude subjective observations of in-plane tearing under a microscope, it was suggested that the in-plane tearing energy is primarily the work of deforming the individual fibers in overcoming the fiber-fiber bonding and in the rupture of fibers. Using individual fiber tensile data and a purely arbitrary estimate of the volume of fibrous material involved in a tearing fracture, estimates of the work involved in the extension of fibers to their average breaking stress exceeded the measured in-plane tearing energies. It was felt that the maximum in-plane tearing energy might be accounted for largely by the work of deforming fibers and that it may not be necessary to seek significant energy contributions from other sources.

The frequency of rupture of softwood sulfite fibers was two to three times greater in 80% aspen kraft blends than in 100% softwood sheets. Along with the increased frequency of rupture, the in-plane tearing energies were higher than predicted by a linear relationship between tearing energy and blend composition. It was concluded that the increased rupture frequency occurred principally because of better interfiber bonding in the high hardwood content furnishes, but that an independent effect related to fiber length could be involved as well. The fact that the increased rupture of softwood fibers occurred along with a favorable increase in the in-plane tearing energy is offered as evidence that the tearing energy is related strongly to work associated with the fracture of fibers.

The Elmendorf tearing energy measured in single sheet tearing tests was always observed to be greater than the in-plane tearing energy. The difference between the two tearing energies was small in the stronger sheets and became greater as the interfiber bonding became poorer. A hypothesis that the in-plane tearing energy is related principally to the load-deformation work of the fibers would also apply therefore to the Elmendorf test for well-bonded sheets. For sheets of lower strength, other means of energy dissipation may be important in the Elmendorf tearing process.

Evidence from both this work and the literature suggests that the tearing energy of pulp blends may always be equal or greater than the average values calculated from the tearing energies of the component pulps. In this work, the in-plane tearing energy of 50:50 mixtures of hardwood and softwood pulps were as much as 30% greater than the average tearing energy of the component pulps. The tensile strengths and apparent densities of the mixed furnishes were equal to or slightly less than the linear averages.

In the blending of hardwood and softwood pulps, one has the ability to control the extent of interfiber bonding along with fiber length distribution. These two factors can be synergistic with respect to the tearing properties of the sheet and thereby provide the opportunity to optimize the tearing quality of paper relative to other properties of interest.

The acquisition of in-plane tearing data has emphasized the fact that the tearing property of paper must not be defined solely by the Elmendorf test. In any further studies of the tearing quality of paper, some emphasis must be placed early on the type of tearing failure which is of principal interest and is to be studied.

INTRODUCTION

From its very beginning, a major part of the hardwood project dealt with the property of tearing strength. The emphasis on tearing strength originates with the low tearing strengths associated with the short fiber length hardwood pulps.

Much of the early work was based on the hypothesis that tearing strength would be improved if the strength of the individual fibers were increased. Although this was a reasonable assumption and evidence pointed to an association between low tearing strengths and low fiber strengths, it nonetheless was a most difficult hypothesis to prove. The zero-span tensile strength was used as a measure of the average strength of the individual fibers.

The first experimental approach (1) involved the use of pulps of different yield. Higher zero-span tensile strengths were obtained for the higher yield pulps if the zero-span strengths were determined on sheets containing a constant number of fibers. On the same constant number of fibers basis, the maximum tearing strength, obtained by adding increasing amounts of locust bean gum to the furnish, also increased with increasing yield.

For aspen pulps prepared at different yields by both the kraft and NSSC processes, the curves relating the maximum tearing strength to the zero-span tensile strengths on a constant number of fibers basis were similar in shape but displaced along the zero-span strength axis. The NSSC pulps had similar maximum tearing strengths compared to the kraft pulps but had approximately 30% higher zero-span tensile strengths. Thus, even on a constant number of fibers basis, no firm relationship between fiber strength as measured by the zero-span test and maximum tearing strength could be claimed.

When zero-span tensile strengths and maximum tearing strengths were compared at constant basis weight using pulps of different yield, again no definite correlation between these two factors could be established. In fact, at constant basis weight, the maximum tearing strengths were very much the same despite differences in yield and zero-span tensile strength. The sole exception was a very low yield, low strength pulp for which a low maximum tearing strength was also obtained.

There are numerous problems associated with an experimental program aimed at determining the effect of fiber strength on maximum tearing strength. There is the obvious difficulty of varying fiber strength without varying any other important property of the fiber. It would appear that this early work raised some important questions about the fiber strength to tearing strength interrelationship. In-plane tearing strength behavior (to be discussed later) would suggest that the maximum Elmendorf tearing strength may not be related at all to fiber strength over a range of fiber strengths typical of many commercial pulps. It would seem much more likely that the maximum in-plane tearing strength could be dependent on fiber strength. This maximum, however, is reached at a high degree of bonding where the Elmendorf tearing strengths may be well below their maximum values. It is still a reasonable assumption that fiber strength is a factor in determining the energy required in the fracture of paper under certain circumstances.

Later in this study of hardwoods, the question of the potential for fiber strength improvement over that of commercial pulps was explored (2). This too proved to be a difficult problem. Using aspenwood, it was concluded that the maximum potential strength of aspen fibers is not very much greater than the strength of fibers taken from the best commercial pulps. When considered in terms of breaking load, it was concluded that the maximum possible strength is only slightly greater than the best values observed for pulp fibers. On a breaking stress basis, it was felt that pulp fibers may reach only about 70% of the maximum possible breaking stress, but this was somewhat unrealistic since the increase in stress was due to a decreasing cross-sectional area. It was impractical to produce fibers having maximum breaking stresses since this might well result in pulps of very high alpha-cellulose content having poor bonding properties.

A number of attempts were made to define the tearing strength to fiber length relationship. Although other factors could not be held absolutely constant, as a first approximation, one could conclude that the maximum tearing strength is linearly related to fiber length (3). Since fiber lengths are distributed over a rather broad range in the usual pulp, the usual attempts to relate fiber length to maximum tearing strength involved the use of either the number average or the weighted average fiber length. It is probable that no average value is entirely suitable for correlation with tearing strength. There appears to be no further evidence to date which argues strongly against the assumption that fiber length and tearing strength are, as a first approximation, linearly related.

At a rather late stage in this program (4), it was judged feasible to attempt a correlation of tearing strength with only three principal factors: fiber length, fiber strength, and the extent of fiber-fiber bonding. It was proposed that the total energy expended in a tearing fracture could be related to the sum of two terms. The first was the energy required to rupture fibers which was treated as dependent only on fiber strength and the number of fibers ruptured. A second term considered the energy involved in the frictional sliding of fibers, which was assumed to be dependent on fiber length and relative bonded area. This type of relationship requires numerous assumptions, most of which are subject to serious criticism. An equation was proposed as a basis for further study of the properties of hardwoods and was explored further without success as reported in Progress Report Two.

It appears that, over the years, these studies aimed at improving the tearing strength of short-fiber length hardwood pulps suffered because of an inadequate understanding of the tearing process. The Elmendorf tearing method is certainly complex, and practically no studies have ever been conducted to illustrate the mechanism of the tearing fracture. These earlier experimental studies were almost exclusively empirical in nature, and the results often did not enable definitive conclusions to be drawn.

This report has two principal purposes. The first is to investigate, with the help of an experimental study, the effects of blending hardwood and softwood pulps. The second is to further explore the tearing fracture process in paper from a conceptual standpoint. Together, it is hoped that a better and broader view of the tearing strength property of paper can be developed.

PART I. THE TEARING BEHAVIOR OF HARDWOOD-SOFTWOOD MIXTURES

As a practical matter, hardwoods are utilized primarily in combination with softwoods. A study of the properties of paper prepared with varying hardwood pulp contents is, therefore, of direct interest. From a research point of view, the combination of short- and long-fiber pulps provides an interesting experimental framework from which to study those physical properties of paper which are fiber length dependent, notably, tearing strength.

The usual way of dealing with the physical properties of paper or board prepared from pulp mixtures is to obtain curves of the various properties as a function of the composition of the furnish. The properties of the blended furnish can then be compared with the properties of the component pulps by assuming that the properties are simply additive in magnitude and observing the degree of departure from the additive value. By additive, it is meant that a pulp contributes to any particular property in direct proportion to its content in the mixture. Thus, a plot of the particular property <u>versus</u> composition would be a straight line connecting the values for the separate unblended component pulps. It is in the departure from linearity that one gains first knowledge of the effects of blending.

There is, of course, no reason why any property of paper should be linearly related to the composition of the blended furnish. In many instances, theory would predict a nonlinear property <u>versus</u> composition relationship. In most instances, however, there simply is no useful theory at all which can be applied to pulp blending.

It should be pointed out that any given pulp is already a mixture of fibers differing widely in dimensions and physical properties and that the combining of two different pulps produces a new combination which would usually be even broader in this distribution of fiber properties. Pulps are not yet characterized by sets of distribution curves for the various properties of the individual fibers; hence, studies of pulp blends relative to the amount of each pulp in the mixture is an obvious expedient.

Brecht (5) dealt in a general way with the properties of mixtures of two pulps. He distinguished between three general types of behavior. The first is illustrated by a linear relationship between a sheet property and the percentage of a particular pulp used in a mixture. He indicated that this is the usual situation when the properties of the separate pulps are quite similar. Secondly, there exist sheet property-composition relationships which are nonlinear but which are described by smooth curves falling wholly above or below the straight line of a linear relationship. A third kind of behavior is characterized by sigmoidal curves relating the property to composition. These show an enhancement of a property relative to the linearly calculated value when the mixture is rich in one of the component pulps but poorer than the linear value when the mixture contains larger fractions of the second component.

Brecht concluded that, in the case of stiffness, opacity, and tearing strength, the pulp having the higher value will be dominating in the mixture. He felt that apparent density and breaking length would tend to follow rather linear relationships to composition of the blend, and that the pulp having the lower value of brightness, air permeability, and absorbency would dominate.

Arlov (6) studied the properties of mixed furnishes prepared from different softwood and hardwood pulps and reported that the effects differed with different pulps and with different degrees of refining. He limited his blends to 1:1 mixtures of the separate pulps and under these conditions noted that the greatest departures from linear property to composition relationships occurred with tearing strength where variations from the calculated value (1:1 blend) exceeded 60% on occasion. Tearing strength, in fact, always appears to exceed the linearly calculated values.

The greatest departures from the expected value of tearing strength occurred when a relatively unrefined birch sulfite pulp was mixed with a well-refined spruce sulfite. When both pulps were well refined the tearing strengths of the 1:1 mixtures were rather close to the average of the tearing strengths of the separate pulps.

Arlov concluded that the greatly increased tearing strengths obtained when the relatively unrefined hardwood pulp was added to a much better refined softwood pulp was due to a reduction in bonding which permitted more of the longer fibers to be withdrawn from the sheet rather than be ruptured.

Studies of hardwood-softwood blends are often conducted for the purpose of determining whether the separate refining of the pulps offers any advantage over refining of the furnish after blending. Although a number of such studies are found in the published literature, such experiments do not usually illustrate the basic behavior of blending long fiber and short fiber pulps and will not be considered further here.

PROCEDURES

The pulps used in this pulp blending study were taken from the same high consistency cold storage supply used in the earlier work described in Progress Report Two and are described more fully in that report. Four separate pulps were used and are identified as follows:

A0 - aspen kraft, unrefined, classified.

A20 - aspen kraft, 20 min. refining, classified.

W5 - Weyerhaeuser bleached sulfite, 5-min. refining, classified.

W20 - Weyerhaeuser bleached sulfite, 20-min. refining, classified.

All of the pulps were classified on the IPC Web Former after refining in a Valley beater.

Twenty sets of handsheets were prepared in accordance with TAPPI Method T 205 (50 p.s.i. wet pressing) for each of the above pulps, alone and in various hardwood-softwood mixtures. Each set contained ten handsheets and in all cases each test result represents the average of ten determinations.

An important part of this study involved the measurement of fiber rupture frequency. It was hoped that fiber rupture data could be acquired for both the softwood and hardwood fibers; hence, all of the handsheets were prepared with 0.5% additions of both dyed softwood and dyed hardwood fibers. Two direct dyes were selected of different color to permit easy identification of the two different fibers. However, the photographic procedures used in this study did not properly record the positions of the hardwood fibers and this part of the experiment was abandoned. Pontamine Fast Rubine B was used to tag the softwood fiber and a Pontamine Fast Blue was used for the hardwood. Neither dye showed any tendency to bleed in xylene which was important in their selection for this work.

The fiber dyeing procedure was simple but time consuming. About 15 grams of pulp were soaked overnight in a liter of distilled water containing two grams of dye in solution. The pulp was then collected on a Buchner funnel and washed until the effluent was reasonably free of color. The fiber pad was then redispersed in two liters of tap water and allowed to soak for a period of about 24 hours followed by refiltering and washing. This procedure was repeated several times until no further bleeding of dye occurred in tap water. Of the two dyes used, the Pontamine Fast Rubine B was most stable to bleeding in tap water and appeared to be held strongly by the sulfite fiber. Both dyes bled more readily and did not show any sign of reaching a state of nonbleeding when washed with demineralized water. Hence, all sheetmaking procedures were conducted in tap water. It was also noted that dyed "fines" collected on the filter paper during the washing of these pulp pads indicating that these pulps were not strictly "fines free."

Fiber rupture data were obtained on all of the in-plane tearing specimens for three of the four series of blends and on a special set of notched tensile specimens In previous work, it was quite apparent that subjective estimates of fiber rupture frequency could be very difficult to make and could be totally unreliable in many instances. In this work, it was felt that an accurate method of determining fiber ruptures was needed even though a smaller total number of fibers might be involved. The method used here involved photographing of the specimens prior to rupture to obtain a record of the initial dyed fiber positions throughout the sheet.

Basis weight and caliper were determined for all handsheets in the conditioned atmosphere and all of the specimens were cut to proper size. All of the specimens were then removed from the conditioned atmosphere and brought to the prevailing low relative humidity in the unconditioned atmosphere where the photographic work was carried out. Each specimen to be photographed was placed between glass plates and xylene was admitted until the sheet was essentially saturated. A length of approximately 3/4 inch of specimen was photographed on 5 x 7 sheet film at a magnification of 8.2. The best image was obtained when the specimen was backed by a white diffuse material such as paper with the light directed downward onto the top of the slide. The dyed fibers throughout the entire thickness of the sheet were visible and could be recorded photographically in this way. The photographed specimens were allowed to dry until thoroughly free of xylene. All of the specimens were then conditioned for 24 hours at 15% R.H. and 73°F. before being reintroduced into the standard test atmosphere (50% R.H., 73°F.) for reconditioning and physical testing.

All of the in-plane tearing strength data were obtained on photographed specimens. A total tearing angle of 12° was employed and the integrated energy was determined over a tearing length of 5 cm.

Special tensile specimens for rupture frequency analysis were prepared by punching semicircular notches of 1/4-inch diameter at opposite edges of 1-inch wide specimens to produce a necked-down width of 3/4 inch.

All of the tensile data were obtained on specimens of 1-inch width using the Instron tester and an initial span of 4 inches.

Elmendorf tearing strengths were determined only on single sheets to avoid any possible effect of multiple sheet tearing on the results. Notched tensile strengths were obtained for all handsheets but since only a few of the specimens were xylene treated it was possible to determine whether the xylene had any influence on the test data. Although the regular tensile and notched tensile strengths differed, it was concluded that the xylene transparentizing had no effect on the result. This is the same conclusion reached by Helle (7) who followed substantially the same procedure in his determination of tearing fracture frequencies.

To determine the effect of the dye on the sheet strength, six handsheets were prepared from each of the dyed pulps. The pertinent data (not presented here) showed that the dyeing procedure caused reductions in the tensile strength of the handsheet ranging from no change for the 20-min. aspen to a maximum of 15.8% for the 5-min. softwood sulfite. Sheet density also decreased with decreasing tensile strength and it must be concluded that the process of dyeing did affect the fiber. The earlier observation that there was an additional loss of fines during the extensive washing of the pulps may have some bearing on the matter of strength loss. The loss of extremely fine, probably colloidal, materials and, possibly, water-soluble carbohydrates was proposed as causing the rather large reductions in tensile strength that occurred when pulps were fractionated and recombined (8). It is possible that the loss in strength might be related as much to the further loss of fines as to the presence of dye on the fiber. Since the results of these fiber fracture studies are used in a relative, rather than an absolute sense, a change in the bonding quality of the fiber with dyeing, though undesirable, is not very serious.

Fiber ruptures in the broken specimens (immersed in xylene) can be counted accurately with the aid of the prerupture photograph (see Fig. 1). The only real source of error is carelessness on the part of the operator, especially when the dyed fiber concentration is high. Even with the aid of photographs, the method can be tedious.

There is a problem in establishing a proper means of reporting the fiber rupture data. The most desirable means of reporting fiber ruptures would appear to be as a percentage of some number of fibers which are in a position to be ruptured. Helle (7) also counted the number of fibers which pulled out of the sheet intact. If all of the dyed fibers are very long, this method can be used with reasonable success. Usually, it is quite difficult to obtain an accurate count of the fibers

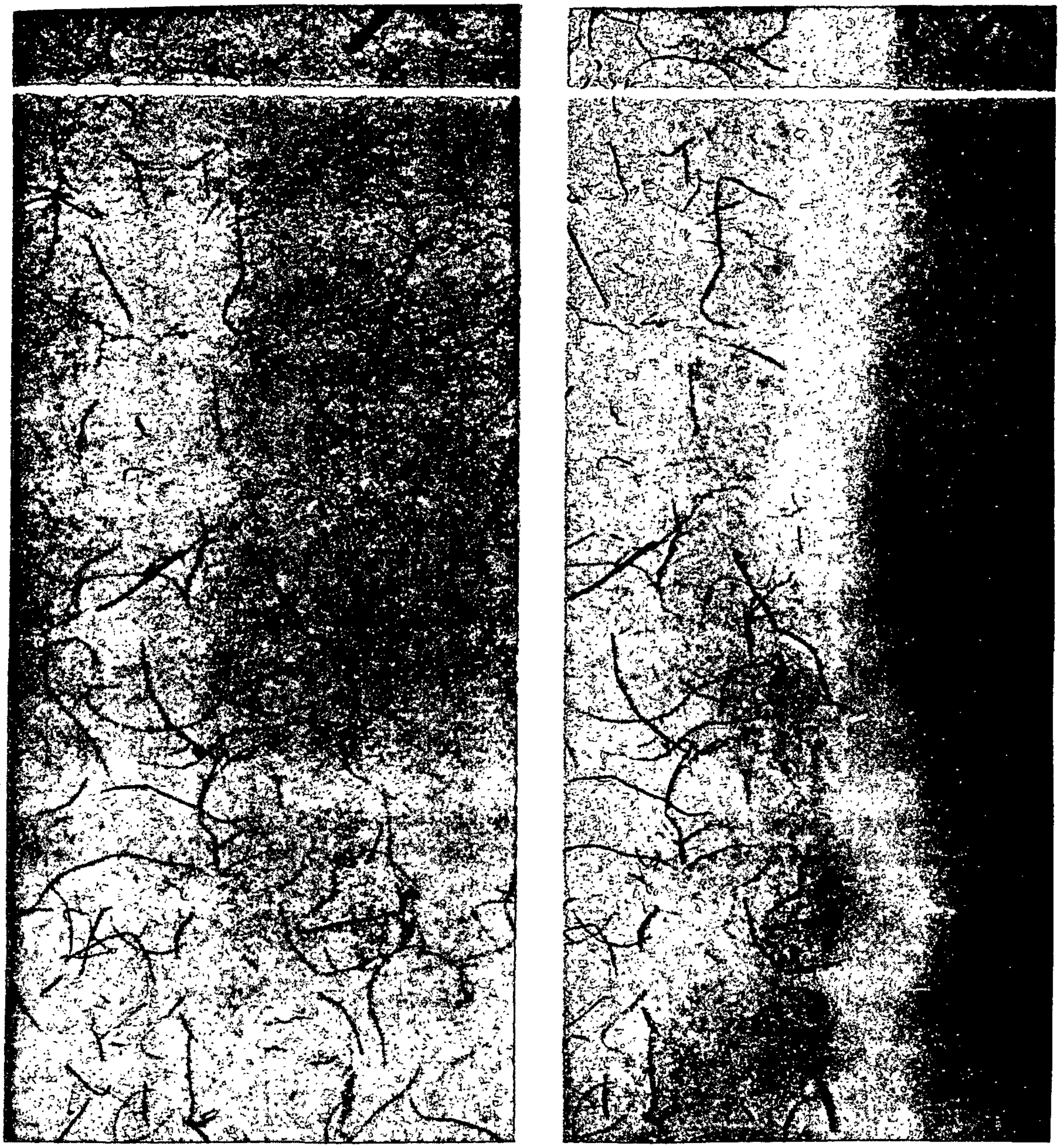


Figure 1. Photographic Record of Handsheet Before and After In-Plane Tearing Fracture

Blend: 80% A-20
20% W-20

which did not rupture. For some fibers, located at the rupture zone boundary, one must decide arbitrarily whether they are properly involved in the tearing fracture process. Some means, however, must be used to account for variations in the numbers of dyed fibers in different sheets. This was done by counting the number of dyed fibers which cross a straight line of given length drawn on the sheet. The ruptured fibers were reported as a percentage of the numbers of fibers which cross a line of length equal to that involved in the fiber rupture counting. These fiber rupture percentages are best treated as relative and not in an absolute sense. The reader should note that in any fiber rupture study, this difficulty of interpreting the results will be present, and will not be overcome by considering the fracture probabilities of long fibers only.

RESULTS AND DISCUSSION

All of the results of this study are presented in Tables I and II. Discussion of these data follows.

FIBER RUPTURE FREQUENCY

The frequency with which fibers are ruptured in the fracture of paper has been used on occasion to draw inferences about the strength properties of paper. Van den Akker, et al. (9) cautiously concluded that the rather high frequency of fiber rupture observed in strong sheets and an appreciable frequency of rupture in weak papers illustrated that the importance of fiber strength in determining sheet strength was probably greater than had previously been suspected. Data relating to the frequency of fiber rupture in the fracture of paper are of interest because they provide one of the principal means of analyzing the fracture mechanism at the present time. Such data should be most useful in dealing with the tearing behavior of paper.

In this study, it was possible to obtain fiber rupture frequency data only for the softwood fibers. The fiber rupture data shown in Table II are given in terms of the total number of observed fiber ruptures within a given fracture length and as a percentage of the number of dyed fibers crossing a line of similar length. This basis is useful mainly for purposes of relative comparison.

The principal observation is the increasing softwood fiber rupture frequency with increasing percentage of hardwood pulps in the mixed furnish. This effect occurred in all three of the blending sets for which these data were obtained. The effect was particularly prominent for the A20-W20 mixtures where the softwood fiber ruptures increased by a factor of three as the hardwood content of the sheet increased from 0 to 80%. This behavior might be explained as a result of better bonding of

TABLE I

SUMMARY OF EXPERIMENTAL DATA

	Aspen 0		Aspen 20	
	WBS 5	WBS 20	WBS 5	WBS 20
Hardwood content, %	0	0	0	0
	20	20	20	20
	40	40	40	40
	60	60	60	60
	80	80	80	80
	100	100	100	100
Basis weight, o.d., g./m.^{2}	61.8	59.7	61.8	59.7
	62.0	59.6	61.4	60.0
	63.6	61.4	60.6	60.7
	61.0	60.9	59.5	62.2
	60.9	60.9	60.8	60.7
	60.1	60.1	59.9	59.9
Caliper, µm.	111.0	96.5	111.0	96.5
	112.0	96.5	107.0	96.5
	112.0	102.0	104.0	94.0
	108.0	102.0	96.5	94.0
	106.0	99.1	94.0	88.9
	102.0	102.0	86.4	86.4
Apparent density, g./cm.^{3}	0.56	0.62	0.56	0.62
	0.55	0.62	0.57	0.62
	0.57	0.60	0.58	0.65
	0.57	0.60	0.62	0.66
	0.58	0.61	0.65	0.68
	0.59	0.59	0.69	0.69
In-plane tear, g.-cm./cm. (at 60 g./m.^{2})	67.5	86.2	67.5	86.2
	70.6	83.9	72.1	83.8
	68.1	72.8	72.5	79.7
	58.2	59.2	69.2	69.3
	47.9	47.3	60.0	55.5
	31.4	31.4	43.5	43.5
Elmendorf tear, single sheet g.-cm./cm. (at 60 g./m.^{2})	112.0	121.0	112.0	121.0
	120.0	112.0	106.0	107.0
	105.0	97.3	104.0	98.1
	91.5	83.1	91.5	85.5
	72.3	65.4	73.2	74.6
	38.4	38.4	45.9	45.9
Breaking length, m.	2550	4490	2550	4490
	2780	4450	3030	4630
	3110	4570	3680	5080
	3410	4600	4480	5540
	3830	4710	5240	6150
	4680	4680	6560	6560
"Notched" breaking length, m.	2650	4300	2650	4300
	3000	4210	--	4370
	3230	4230	3670	4780
	3540	4240	4310	4980
	3850	4300	4770	5210
	4360	4360	5640	5640
Stretch, %	1.5	2.4	1.5	2.4
	1.5	2.1	1.7	2.1
	1.4	1.8	1.8	2.1
	1.3	1.6	1.9	2.2
	1.3	1.5	1.9	2.1
	1.3	1.3	2.0	2.0
Extensional stiffness, kg./cm. (at 60 g./m.^{2})	295	380	295	380
	320	410	340	430
	355	415	360	480
	395	450	440	490
	455	460	495	560
	510	510	565	565
Tensile energy absorption, g.-cm./cm.^{2} (at 60 g./m.^{2})	17.4	46.6	17.4	46.6
	18.7	39.9	23.4	44.0
	20.2	37.2	30.5	47.8
	19.6	32.1	37.8	53.4
	21.2	29.0	42.8	55.7
	24.6	24.6	55.9	55.9

TABLE II

SOFTWOOD FIBER RUPTURE DATA

Notched Tensile Fractures
W20 Plus A0 Blends

Hardwood content, %	0	20	40	60	80
No. of broken fibers	35	23	26	21	30
No. of fiber crossings	260	150	146	145	143
Rupture frequency, %	13.5	15.3	17.8	14.5	21.0

In-Plane Tear Fractures
W20 Plus A0 Blends

Hardwood content, %	0	20	40	60	80
No. of broken fibers	32	11	18	32	28
No. of fiber crossings	281	162	157	157	155
Rupture frequency, %	11.4	6.8	11.5	20.4	18.1

In-Plane Tear Fractures
W20 Plus A20 Blends

Hardwood content, %	0	20	40	60	80
No. of broken fibers	32	27	43	47	50
No. of fiber crossings	281	153	156	161	152
Rupture frequency, %	11.4	17.7	27.6	29.2	32.9

In-Plane Tear Fractures
W5 Plus A20 Blends

Hardwood content, %	0	20	40	60	80
No. of broken fibers	31	27	21	38	48
No. of fiber crossings	392	185	186	180	171
Rupture frequency, %	7.9	14.6	11.3	21.1	28.1

the softwood fiber in the hardwood furnish. This view is supported by the very considerable increase in softwood fiber ruptures when the hardwood pulp was refined and an increased number of ruptures when the softwood fiber was refined as well.

In the case of the AO-W20 blends, an increase in softwood fiber ruptures occurred in the high hardwood content mixtures even though both pulps had similar tensile strengths. This encourages the view that an increase in the rupture frequency should be noted for longer fibers when they are present in small percentages in a short fiber length furnish. This follows from the expectation that very long fibers, perhaps 20 to 30 mm. in length and having normal strengths, would be broken with very high frequency in an ordinary wood pulp furnish because they will experience concentrated stresses over some portion of their length, but little stress at their ends. Unfortunately, the experimental work did not include the case of blending a well-beaten strong softwood pulp with a weak hardwood pulp.

Helle (7) measured fiber rupture frequencies for both Elmendorf tear and tensile fractures and concluded that the fiber rupture frequency was higher in the tearing test. He noted higher frequencies of rupture in tensile testing at higher rates of loading and felt that differences in testing rate might explain the higher rupture incidence in the tearing test. In this study, fiber ruptures were counted for both the tensile and in-plane tests for the AO-W20 mixtures. Although the data are somewhat erratic due to the small number of fibers involved, it must be concluded that the rupture frequencies are quite similar with possibly a slightly higher rupture frequency for the tensile fracture. It seems that any differences in rupture frequency in different tests should be attributed first to differences in the distribution of stresses in and near the zone of fracture and, to a lesser extent, to differences in the rate with which the specimen is fractured.

The increasing rupture of softwood fibers in the high hardwood content furnishes corresponds to a greater than expected in-plane tearing energy for these mixtures. This is a most important observation and is discussed in greater detail later in this report.

SUBJECTIVE OBSERVATIONS OF FIBER RUPTURE PHENOMENON

In the counting of fiber ruptures, some general subjective evaluations of the factors which appear to determine the probability of rupture can be made. It is quite possible that a more thorough analysis of the fractured specimens would lead to a more objective analysis.

A first observation is that fiber length alone is a poor basis for predicting the probability of rupture of any given fiber. A fiber may be broken at a point only two to three fiber widths from an end. This suggests that, in some instances, only one or two fiber-fiber bonds can provide the gripping necessary to attain the breaking load of the fiber. Fibers which may break in this way always appear to be broad, ribbonlike, and probably thin walled.

Fibers which are wirelike, rather narrow in width, and which appear to be thick walled and uncollapsed were very rarely broken, even if they were long and positioned symmetrically across the rupture line.

There appeared to be a rather high probability of rupture if a fiber was curved in the form of a horseshoe and spanned the rupture line with the legs of the horseshoe pointing in the tearing direction. Although it seemed that fibers lying more nearly perpendicular to the rupture line were ruptured more frequently, this was not at all an obvious observation. Occasionally, fibers lying in the tearing direction were broken. It appeared that a great deal of data would be needed to define the relationship between fiber orientation and rupture frequency.

There were several instances where a fiber had obviously been ruptured but where one part of the fiber was lost. This was disconcerting because it was difficult to imagine fracturing conditions in which a small segment would be completely debonded from its contiguous fibers. Later, it was observed that small segments of fibers which fell completely within the zone of fracture were almost totally debonded and it seemed reasonable that some small segments could actually fall from the sheet.

An analysis of the probability of fiber rupture in a tearing or tensile fracture process would, as a minimum, require information about the size and strength of the fiber-fiber bonds, the cross-sectional areas and strengths of the fibers, the length and position of the fibers relative to the fracture zone including an effect of curvature, etc. This would indeed be a complex undertaking in view of the very wide distribution of such properties in a typical pulp.

IN-PLANE TEARING STRENGTH

The in-plane tearing energy data for the various pulp blends are plotted versus blend composition in Fig. 2. The first observation is one which has generally been made in studies of pulp blends, namely, that the tearing strength versus composition curves may be quite nonlinear with tearing strengths considerably greater than the linear average values. For the blends of W5 pulp with either of the aspen pulps the in-plane tear energies for 50:50 mixtures were about 30% greater than the linear averages. Since there are no other data dealing with the in-plane tearing of softwood-hardwood blends, it is not possible to draw a general conclusion that the in-plane tearing energy will always be equal or greater than the linear average value. Of all the physical properties, it appears that one's ability to predict the property of a blend from the property of the components is poorest for tearing strength.

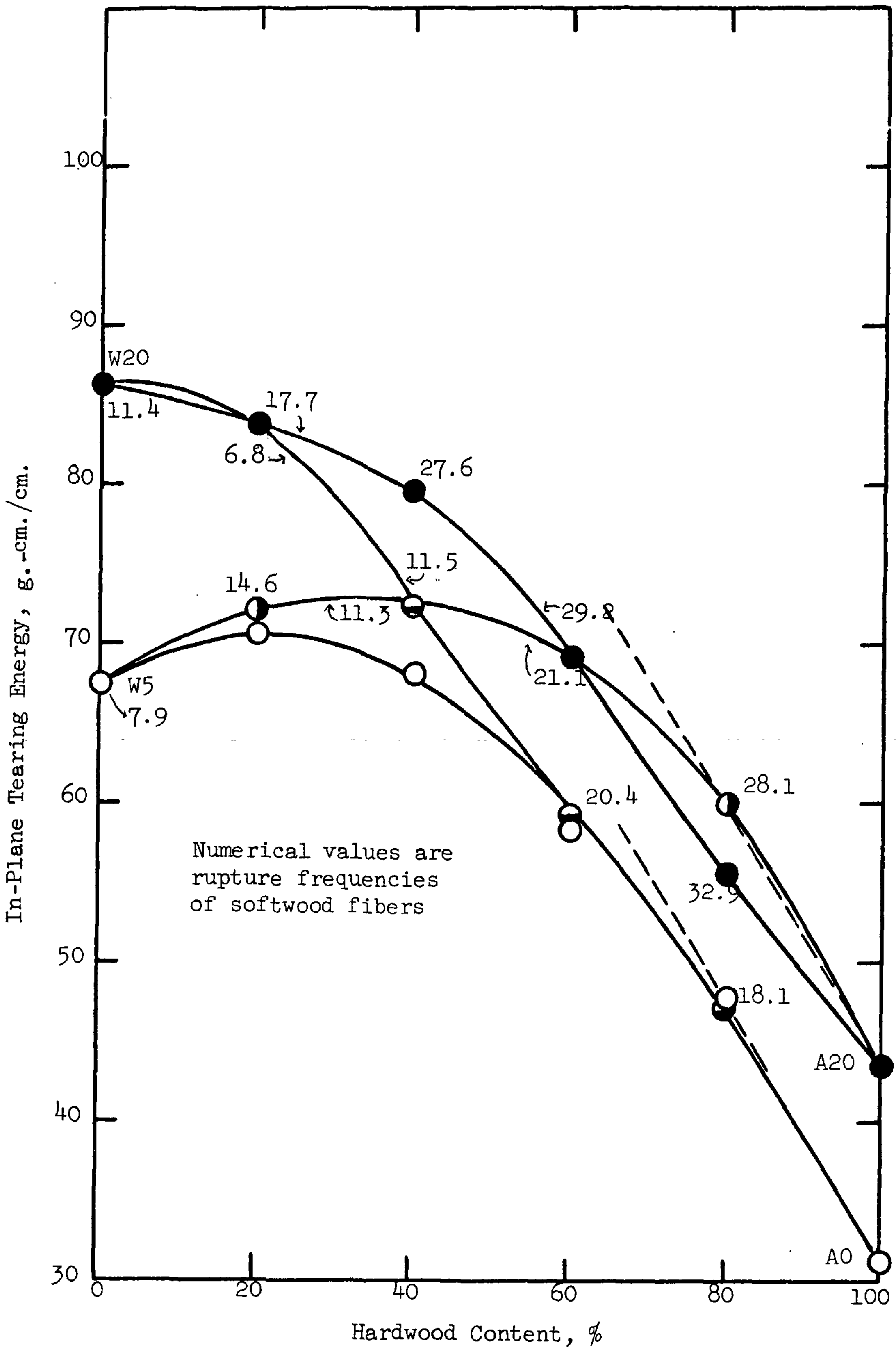


Figure 2. In-Plane Tearing Energy Versus Percentage of Hardwood in Various Hardwood-Softwood Pulp Blends

Tearing strength is a property which can be improved considerably in blends over the values which might be expected from the tearing strengths of the individual pulps.

A number of qualitative observations can be drawn from the data plotted in Fig. 2.

First, it is possible for the tearing energy of a pulp mixture to be greater than the tearing energy of either component. This is a circumstance which does not seem to occur with any other property of the sheet. It apparently occurs for tearing energy because of a desirable interaction between the effect of bonding and fiber length. In the case of the in-plane tearing energy, both improved bonding and longer fibers increase the tearing energy and the synergistic effect occurs with the better bonding of the longer fibers.

It is noted that replacement of the first 20% of hardwood with softwood resulted in an increase in the in-plane tearing energy of about 16 g.-cm./cm. This value did not change much with refining of either the softwood or hardwood pulp. If the replacement of hardwood with softwood were continued until a 100% softwood sheet were obtained, using the same increment of energy, the in-plane tearing energy of the softwood sheet would be about 80 g.-cm./cm. over that of the initial hardwood sheet. Hence, using this extrapolation technique the in-plane tearing energy of the softwood sheet would be 110 to 125 g.-cm./cm. It is most interesting to note that this rather high value may be quite consistent with the maximum in-plane tearing energy for this pulp if reductions in fiber length did not occur with continued refining. A maximum in-plane tearing energy for this pulp with laboratory refining in the Valley beater is expected to be about 110 g.-cm./cm. Thus, it appears that the initial incremental increase in in-plane tearing energy per increment of added softwood (replacing hardwood) may be determined by the maximum possible in-plane tearing strength of the softwood pulp. If the aspen pulp could be refined to develop an in-plane tearing energy of 55 to 60, one might speculatively estimate an in-plane tearing energy for the softwood as high as 135 to 140 if the slope of the curve shown in Fig. 2 remained constant. Eventually, additional refining of the aspen pulp could result in a lower slope, indicating less than the maximum possible contribution of energy from the softwood fiber. The fact that increased refining of the softwood pulp apparently did reduce the energy contribution of the softwood fiber in a hardwood sheet suggests that the incremental energy of 16 g.-cm./cm. for a 20% replacement may be a realistic maximum for the softwood fiber. A most intriguing question is just how this increased energy is to be accounted for. The increasing rupture frequency of softwood fibers in the higher hardwood content furnishes provides a basis for conjecture. It appears that the maximum in-plane tearing energy would occur when an appreciable percentage of the fibers involved in the tearing process were ruptured, probably in excess of the highest rupture frequency noted here for softwood fibers in mixtures with the refined aspen. The correspondence between the maximum in-plane tearing energy and a high percentage of fiber rupture supports the view that the in-plane tearing energy is largely a measure of the work required to deform the individual fibers.

ELMENDORF TEARING ENERGY

The Elmendorf tearing energy data have been plotted _versus_ blend composition in Fig. 3. It may be noted that the Elmendorf tearing energies of the blended furnishes are always greater than the values predicted by a linear combination of the values for the separate pulps, and that the departure from linearity for the various blends is similar in magnitude to those noted for the in-plane tearing energies shown in Fig. 2. The two tests do not rank the samples in the same way, however.

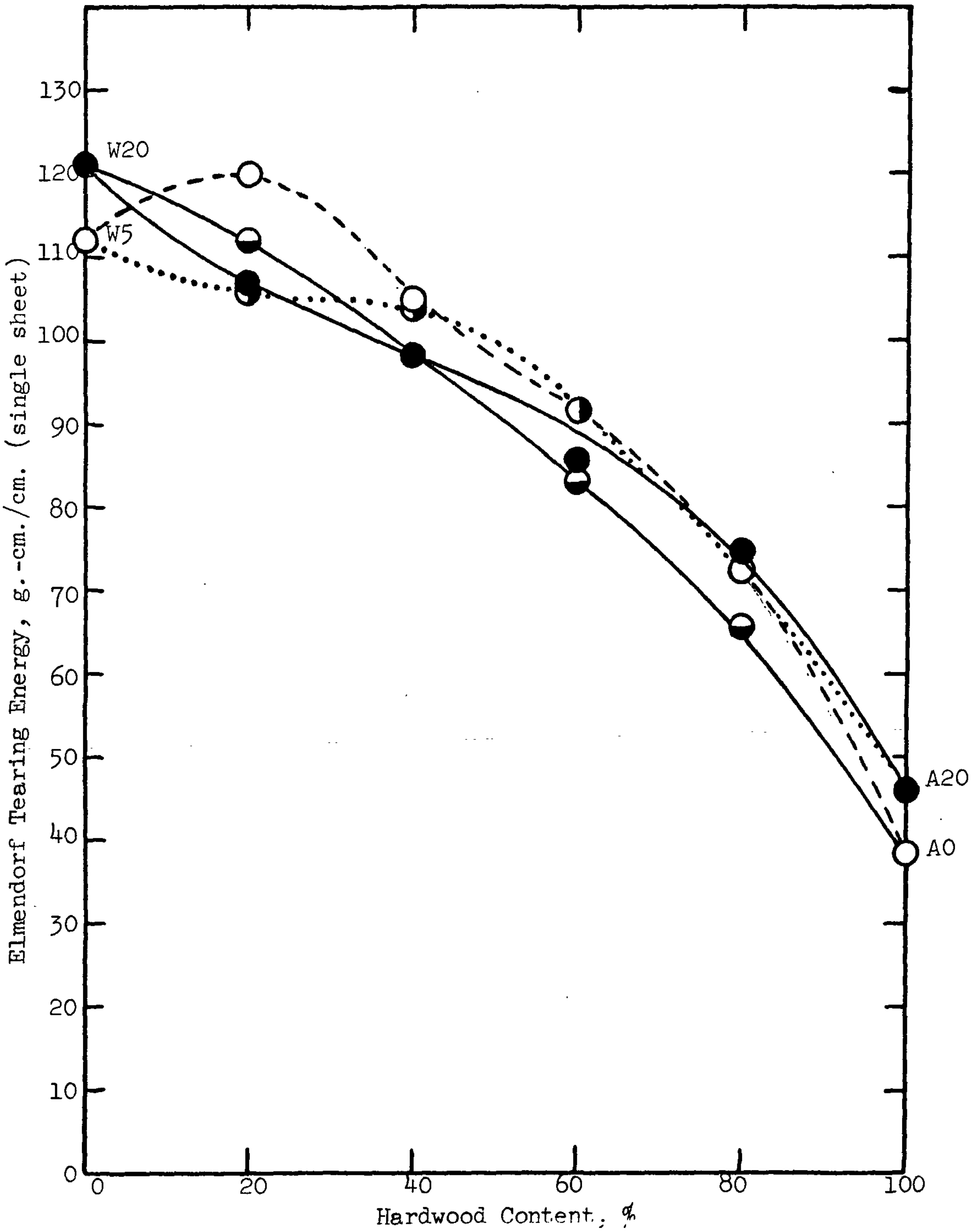


Figure 3. Elmendorf Tearing Energy Versus Percentage of Hardwood in Various Hardwood-Softwood Pulp Blends

The very similar Elmendorf tearing energy of the softwood pulp, whether refined for 5 or 20 minutes, is unusual. The usual expectation is that the Elmendorf tearing energy (in the presence of fines) at the 20-minute refining level might be only half of the value noted for the 5-minute refining interval. A possible explanation for this result is that, in the absence of fines and for single-sheet testing, the tearing energies for the two pulps fall on alternate sides of a maximum value. Reference to data presented in Progress Report Two shows that a maximum may indeed fall somewhere between the two beating intervals for single-ply tearing tests. With 5-ply Elmendorf testing, the more typical reduction in tearing energy with refining is noted even for these classified pulps. The Elmendorf tearing energy for 5-ply testing was about 65% higher than the single sheet result for the 5-minute refining interval and about 40% higher for the 20-minute interval. In this study, only single-sheet Elmendorf tearing tests were performed to avoid the kind of error described above.

The differences between the measured tearing energies obtained by the Elmendorf and the in-plane tearing methods are of interest since the different tests do not measure the tearing property of paper in the same way. It is known that the Elmendorf and in-plane tearing methods can yield essentially similar energy values when the sheets are rather well bonded. This is confirmed in these experiments. In weaker sheets, the Elmendorf method yields higher results. A careful study of the data given in Table I indicates that the ratio of the Elmendorf to the in-plane tearing energies decreases with increasing tensile strength, increasing elastic modulus, and with increasing hardwood content of the furnish. The ratios ranged from highs of about 1.7 to lows of about 1.05. It should be recalled that these ratios relate to single-sheet tearing by the Elmendorf method and that much higher ratios are possible with multi-ply Elmendorf tearing. Attempts to examine these differences in greater detail were not very fruitful whether they were treated in terms of ratios or as absolute energy increments.

One looks increasingly toward the relationship between the Elmendorf tearing energy and the extent of interfiber bonding as a characteristic which may be peculiar to the Elmendorf method. The additional energy in the fracture process which may be introduced at lower bonding strength levels may be a complication rather than an inherent and necessary part of a primary fracturing process.

The curves of Elmendorf tearing energy *versus* composition of the blend are more involved than the in-plane tearing energy curves and more difficult to interpret. The curves do reflect the negative effect of increased bonding strength on the Elmendorf tearing energy. The Elmendorf test rates the softwood pulps higher relative to the hardwood pulp than does the in-plane test. Some of the highest Elmendorf tearing energies of all the blended furnishes occurred in the weak W5-AO blends, which showed the lowest in-plane tearing energy. Since the frequency of softwood fiber rupture is undoubtedly lowest for these handsheets, an interpretation using the frictional work concept would apply since the breaking of fewer fibers means an increase in the number of fibers which can contribute to frictional drag work. The dilemma at this point, however, should be clear to the reader. The same concept cannot be applied to both tearing tests. A frictional work concept may be much more important or even substantially limited to Elmendorf tearing.

A further complication lies in the thought that one's justification for improving tearing strength measured by the Elmendorf method may be poor when viewed with respect to the use requirements of the sheet. Apparently, it has never been claimed that the Elmendorf testing method simulates failure in use. Hence, before much further work is conducted involving tearing strength, one should attempt to establish a sounder basis and approach to the problem.

TENSILE STRENGTH

The relationships between tensile strength and the percentage of hardwood in the furnish are shown in Fig. 4. In all of the blends, the measured tensile strengths are lower than the values calculated by linear averaging of the tensile strengths of the component pulps. In the blends prepared from the more refined softwood pulp, the reduction in tensile strength relative to the linear average values is quite small and, for most purposes, can be considered negligible. For the lesser refined softwood, W5, the tensile strength of the blended furnishes are lower than the linear average values by larger amounts, as much as 12.3% less for the 50:50 mixture of A20 and W5 pulps. Considering only these data, one might conclude that it is undesirable to strongly refine one pulp of a mixture to the practical absence of refining of the other if best tensile strength development is desired.

One might postulate that the average tensile strength would not be reached if the two pulps in a blend varied considerably in the load-elongation properties of their individual fibers. If some fibers are much more easily extended than others, they may not develop significant stresses at given levels of strain and would not therefore be expected to carry their share of the tensile load. Thus, the greater the degree of heterogeneity in the load-extension characteristics of the individual fibers, the greater the probability of a lower tensile strength. If in the refining of a pulp, the load-extension characteristics of the fibers are changed to develop greater heterogeneity in a blend, the effect on tensile strength could be undesirable compared to the refining of both pulps.

Arlov (<u>6</u>) found only small variations in the tensile strengths of hardwood-softwood pulp mixtures compared to the linear averages of the strengths of the component pulps. In his work, the differences seldom exceeded 6% and in mixtures of a softwood

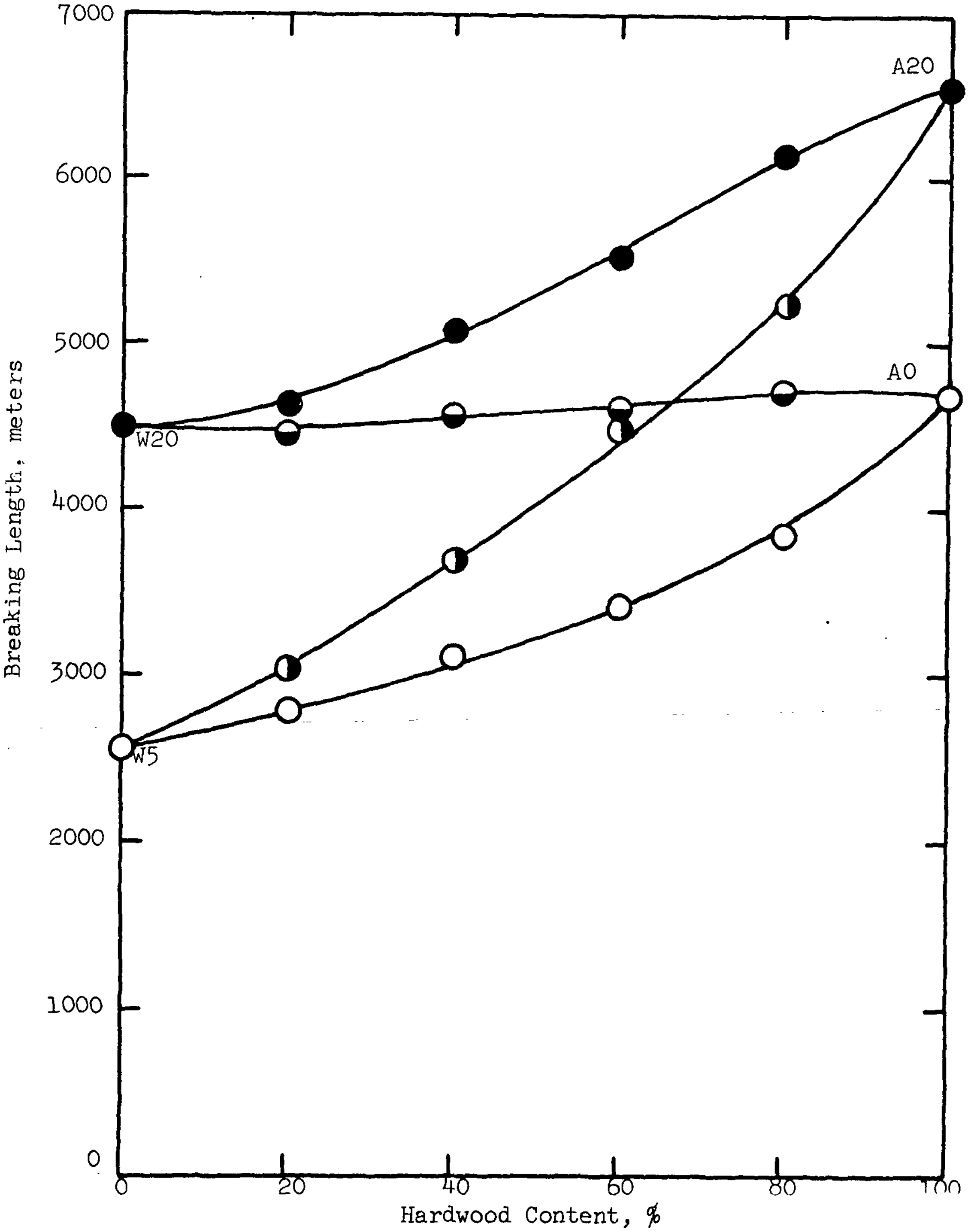


Figure 4. Breaking Length Versus Percentage of Hardwood in Various Hardwood-Softwood Pulp Blends

sulfite pulp with a birch kraft pulp, he found tensile strengths which were greater than the linear averages.

It seems most likely that the tensile strength behavior in the blending of two pulps is determined either by the properties of the individual fibers or by geometric factors which could affect the bonded area. Bonded area measurements were not made on the blended pulp handsheets. Swanson (10) studied the effect of varying amounts of locust bean gum on blends of different composition prepared from unrefined softwood sulfite and aspen sulfite pulps. Although the data were somewhat erratic, in all cases the tensile strengths of the mixed furnishes fell below the linear averages indicating that the tensile strength behavior in blending was not very much affected by differences in bonding strength.

APPARENT DENSITY

An examination of the data shows that the lower than linear average tensile strength of the A20 plus W5 blends corresponds as well to a lower than linear average apparent density. It may not be correct to associate the lower density to the lower tensile strength. Arlov found no general relationship between the apparent density behavior and the tensile strength behavior in pulp blending. In fact, Arlov only rarely obtained apparent densities which differed by more than 2% from the linear averages. Also, he often found the density of a hardwood-softwood mixture to be greater than the linear average. This he attributed to better packing which is possible with particles of different size.

In an unpublished study by the writer involving the blending of softwood kraft pulp with groundwood, it was found that with refined kraft pulp an excellent linear relationship was obtained between the apparent density of the sheet and the kraft content. With unrefined kraft pulp, the apparent densities of the blends were as much as 8% below the linear averages.

It is probably safe to assume that the apparent density of mixed furnishes will be linearly related to the composition or slightly below the linear value in most instances.

OTHER PROPERTIES

The extensional stiffness is an elastic constant represented by the initial slope of the tensile load-deformation curve. It is equivalent to the product of the elastic modulus and the thickness of the specimen. The extensional stiffnesses of the blended pulps fell slightly below the linear averages for three of the pulp blending systems. For blends prepared from the two more highly refined pulps, the extensional stiffnesses were as much as 5% greater than the linear averages.

Although measurements of bending stiffness were not obtained for these specimens, it is possible to estimate the behavior of bending stiffness in blending from the extensional stiffness and the apparent density data. It can be shown that the ratio of extensional stiffness to the square of the apparent density should be approximately proportional to the flexural rigidity of the sheet. If both the apparent density and extensional stiffness of the blended furnishes were found to be linearly related to blend composition, one would expect the flexural rigidities to be nonlinearly related to composition with values below the linear averages. Actually, a rather cautious analysis of these data suggests that the flexural rigidity of the blends will be very nearly a linear function of composition for the unrefined aspen pulp mixtures and very slightly greater for blends prepared with the refined aspen pulp.

The flexural rigidity of the aspen kraft pulp would be considerably greater than that of the softwood sulfite due to the much greater extensional stiffnesses for the aspen pulp at similar apparent densities. Since refining of the aspen pulp increased the sheet density considerably but without much increase in the extensional stiffness, the effect of refining of the aspen was calculated to reduce its flexural rigidity by about 20%. Refining of the softwood sulfite pulp could have increased the flexural rigidity of this pulp by a small amount (probably less than 4%). Brecht's observation that the bending stiffness of a blended pulp would be greater than the linear average is not well supported by these data.

It may prove helpful to examine the curves of all measured properties _versus_ blend composition on a single plot. The various curves for the blending of Pulps A20 and W5 are shown in Fig. 5. The actual values for each property are directly proportional to the arbitrary units in all cases. Hence, each curve correctly shows the change in the particular property on a percentage basis. It may be seen quite clearly in this figure that the tearing energy behavior is unique and unlike that of any other property.

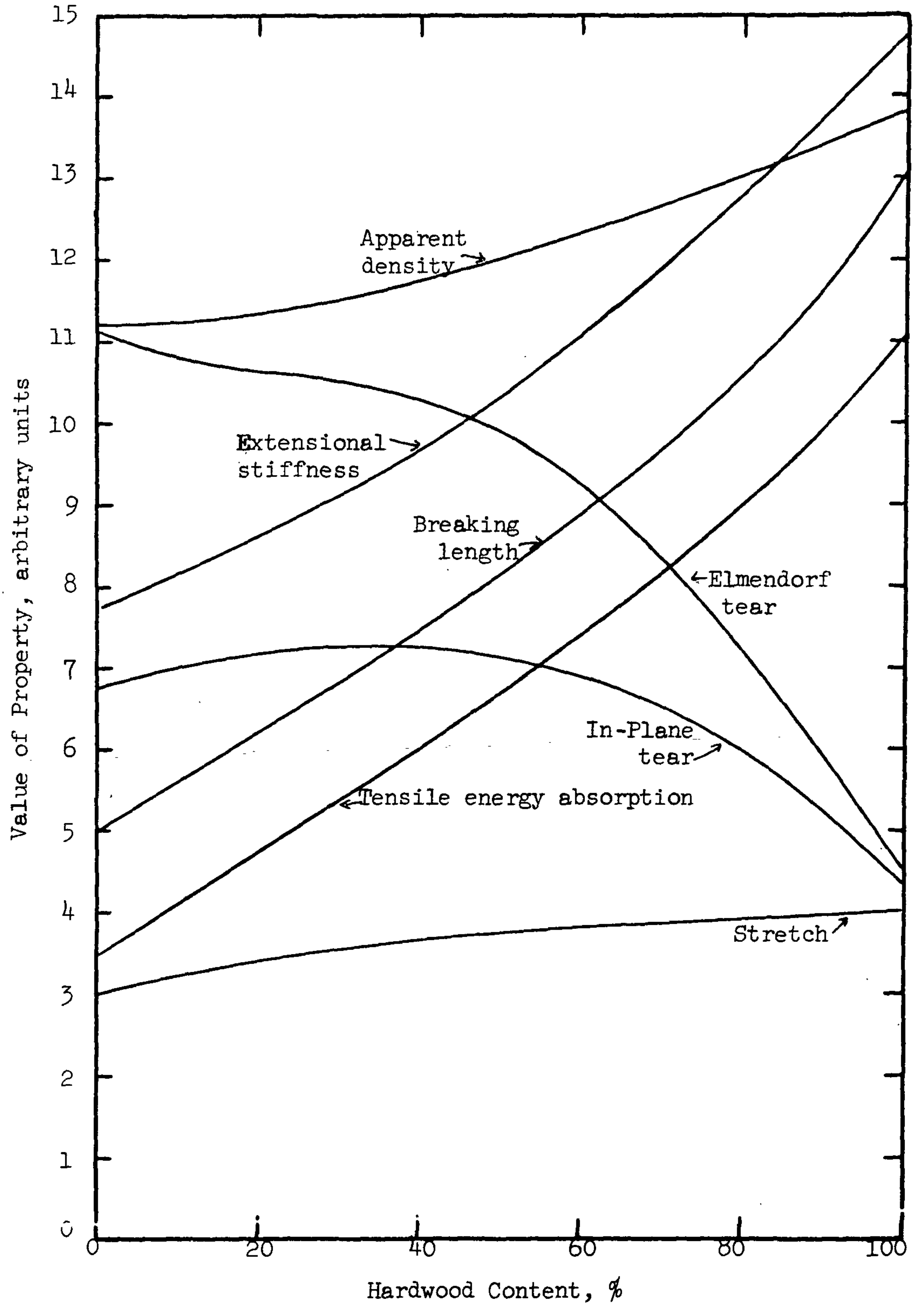


Figure 5. The Various Sheet Property Versus Percentage of Hardwood Relationships for Handsheets Prepared from Pulps A20 and W5

PART II. SELECTED TOPICS ON THE TEARING STRENGTH OF PAPER

Until rather recently, reference to the tearing strength of paper implied measurements obtained with an Elmendorf-type tearing tester in which the forces are applied rapidly and essentially normal to the plane of the sheet. Furthermore, for most papers, it is customary to tear a number of sheets simultaneously, a procedure which can affect the result (11). The tearing process was, perhaps, considered to be much too complex to warrant an experimental study of the tearing fracture mechanism. To date, no significant study of the mechanism of the tearing fracture process can be found in the literature although numerous studies of the tearing strength of paper have been made.

For many pulps, the frequent observation that increased beating and wet pressing reduced the Elmendorf tearing strength, while the tensile strength increased, led to the general assumption that these properties are inversely related. Such inverse relationships were almost always observed for long-fiber length pulps. The optimization of tearing and tensile strength still is an important consideration in the treatment of pulps for papermaking. Perhaps more emphasis should have been placed on the fact that an inverse relationship between Elmendorf tearing strength and tensile strength was not always observed in the case of hardwood pulps. For many hardwood pulps, the Elmendorf tearing strength increased with increased beating and wet pressing as did tensile strength. In other instances, tearing strength did not reach a maximum value until considerable refining of the pulp occurred after which a decrease in tearing strength with further refining became evident. Such behavior is often associated with pulps having rather poor tensile strengths in the unrefined state, such as the alpha pulps.

The usual first step one takes when attempting to study the process of rupture of a material is an examination of the fracture surfaces. In the fracture of paper, the general observation is that numerous fibers are withdrawn from the structure and appear to be largely intact whereas others break. Further, it can be observed that the relative incidence of fiber rupture increases as the strength of the sheet increases.

Without much hope of describing in detail the specific processes of energy dissipation in the complex tearing fracture of paper and faced often with a very pronounced loss in tearing strength as the tensile strength increased with increasing bonding, researchers in the field sought a valid explanation for such behavior. Of particular interest, was the explanation offered by Van den Akker in 1944 (12). Van den Akker related the increasing fiber rupture to the reduction in tearing strength and suggested that less energy may, in fact, be required to break a fiber than to extract or withdraw the fiber from the sheet. Since the force on the fiber must clearly be smaller if the fiber does not break, it was suggested that the smaller force acted over a much greater distance, possibly over distances which are appreciable fractions of the length of the fibers as opposed to the comparatively small extensions associated with the extension of fibers to the point of rupture.

It was further suggested that the resisting force involved in fiber pullout was a "frictional force." This could be defined as a force resisting the motion of two bodies in contact but without bonding or adhesion between the bodies. Although Van den Akker offered this explanation in the hope that it would lead to further investigation, his theory tended to be accepted directly without experimental verification.

A principal difficulty in seeking a better understanding of tearing energy dissipation involves the frictional work. The question is not whether frictional effects are involved in the tearing of paper. They undoubtedly are. It is a matter of establishing the magnitude of the frictional drag energy in relation to the total tearing energy. The frictional energy concept can rather successfully explain many, if not most, of the phenomena observed in the tearing behavior of paper. As a concept, it is extremely versatile. Increased fiber-fiber bonding, for example, can either increase or decrease the tearing energy depending on whether an increase in the frictional drag force is more or less important than the change in the number of ruptured fibers.

Attempts have been made to establish mathematical expressions for tearing energy based on the relative energy contributions of ruptured and pulled-out fibers. Perhaps the first of these is that of Kane (7). Wilder derived a similar expression (4). So many assumptions are required in the development of such expressions that it is questionable whether they are of any value at this time. One still requires more definitive descriptions of the various mechanisms of energy dissipation in the tearing fracture of paper.

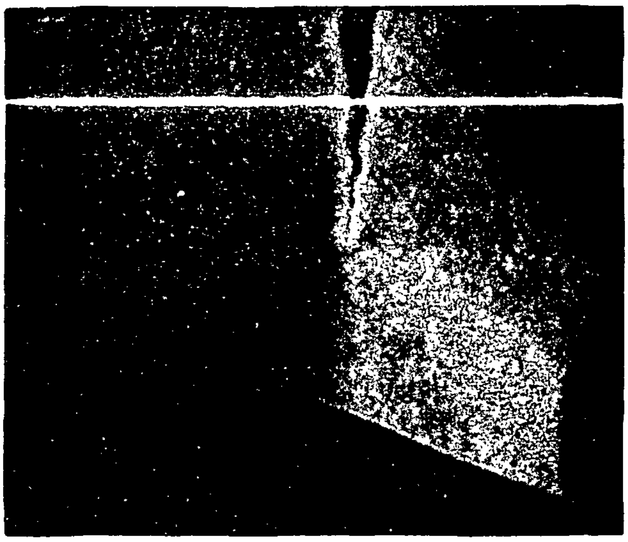
Within the past few years, new information has become available in two principal areas which bear directly on the tearing energy problem. First, there is the information now available dealing with the in-plane tearing of paper (14) and, secondly, an increasing quantity of individual fiber tensile test data are being obtained.

For purposes of analysis, the process of tearing, one can argue, should proceed in the least complicated manner possible. Thus, one should strive to measure the tearing fracture energy in a manner which accomplishes the fracture with a minimum expenditure of energy. It might be assumed that the additional energy in excess of some minimum value would represent a complicating contribution. The in-plane tearing of paper produces the fracture with less energy than the Elmendorf and, in this sense, should be a helpful research test. It may, in fact, also be better related to the kind of tearing which is involved in the use of the product.

The in-plane tearing of paper was studied by Unger (15) with emphasis on the force to tearing angle relationship. Consideration of in-plane tearing in terms of tearing energy was the subject of a study by Van den Akker, et al. (14). They noted that the tearing energies were not greatly affected by tearing angle over a rather comfortable range of angles for a number of different commercial papers. In tearing by this method, the forces are essentially applied in the plane of the sheet. The in-plane tearing mode is shown in Fig. 6. In-plane tearing can be conducted using a tensile tester equipped with special clamps for proper gripping of the specimen and preferably also equipped with an integrator to provide a direct measure of the tearing energy (14). Since the in-plane failure is more directly comparable to a tensile failure with stresses more nearly in the plane of the sheet, the energy measured in the in-plane tearing test should be more readily interpreted with respect to the familiar in-plane tensile properties of paper.

Perhaps the most important initial observation in the study of in-plane tear is that the tearing strength is low for papers of low tensile strength and increases along with increasing tensile strength over much of the beating interval quite contrary to the usual Elmendorf tearing behavior. With continued beating, the in-plane tearing strength may reach a maximum value. For some pulps, no maximum in the in-plane tearing strength may be noted within the usual laboratory refining intervals. The frequency of rupture of fibers would presumably increase steadily throughout the entire refining period and, in the case of the in-plane tearing strength, one must question an assumption that less energy is involved in the rupture of a fiber than in pulling it from the sheet intact.

There are a number of reasons which might be advanced to account for the differences between the Elmendorf and in-plane tearing energies. These include factors such as differences in tearing rate, in bending or flexure of the sheet during tearing, in splitting or delamination in tearing, the frictional rubbing



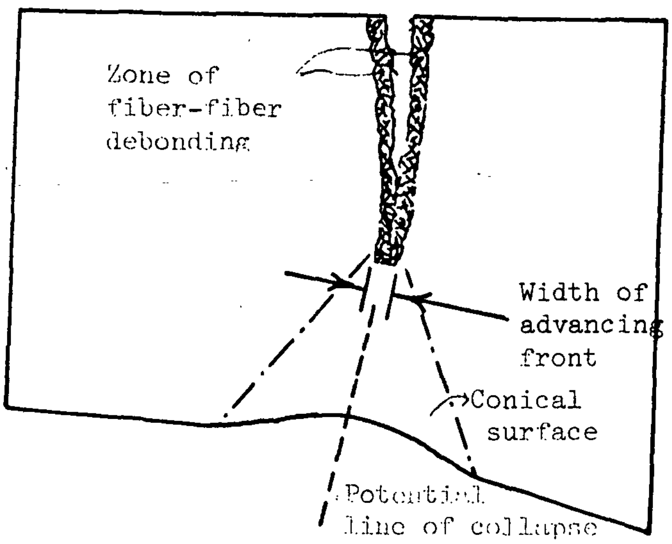


Figure 6. Illustration of the Zone of Fiber-Fiber Debonding in the In-Plane Tearing of an 80% A20 and 20% W20 Handsheet. The Magnification is Approximately 3.2 and the Tearing Angle is Approximately 10 Degrees

of the torn portions of the sheet as they move past each other, the distribution of stress over a wider area in one test compared to the other, etc.

The introduction of the in-plane tearing method introduces the question of which test best describes the tearing behavior of paper with respect to tearing failure in use. It is a question having important implications in research aimed at improving this property of the sheet. This is, in itself, a subject of research interest and it will not be considered further here.

SUBJECTIVE OBSERVATIONS OF THE TEARING FRACTURE PROCESS

One aspect of the tearing fracture process can be observed by propagating a tearing fracture under a microscope when the sheet is partially wetted with xylene. The change in opacity which accompanies the fracture of fiber-fiber bonds can readily be seen. It was noted that, for in-plane tearing, the bond breaking seems to proceed along a front having a rather well-defined width (see Fig. 6). The width of the advancing front is reasonably constant initially for many papers. With continued separation of the two portions of the sheet, this width increases somewhat. Attempts to estimate the width were not entirely successful. It was, however, judged to be about 1 mm. for the handsheet shown in Fig. 1. The significant observation is that much of the debonding occurs simultaneously along an advancing front. Small segments of fibers which lie wholly within this debonding zone are often observed to be almost totally debonded. It is not unusual, therefore, that short dyed fiber segments, which were known to fall within the fracture zone, could not be found upon inspection of the fractured specimen. The debonding process seems to be unusually complete within this zone.

It was noted also that, in the in-plane tear, the fiber-fiber debonding does not occur strictly in the plane of the sheet. The forces appear to act partially within the conelike portion of the untorn specimen. Fibers lying on the convex surface of the conelike portion are sometimes seen to be peeled from the surface as the tear progresses. The opacification also can be observed at the concave surface of the cone. In a few instances, the conelike structure was observed to collapse prior to tearing. When this happened, the tear followed the crease and seemed to proceed along a narrower front.

Further subjective observations were attempted with respect to the magnitude of the forces needed to complete the destruction of the sheet after the debonding and opacification occurred. At this point, the fibers were still intertwined and rather little extension of the structure could have occurred relative to the fiber length. Although the magnitude of force was exceedingly difficult to evaluate subjectively, this writer felt that the largest portion of the work of in-plane tearing is involved in the debonding process. Within this zone there is seen to be considerable fiber reorientation and movement; however, the structure at this point is no longer very restrictive to individual fiber motion. If the fiber still remains bonded at its ends in the intact portions of the sheet at the boundaries of the fracture zone it becomes taut with continued separation of the two portions of the sheet leading to further debonding or fiber rupture. One has an opportunity to test subjectively the forces needed to continue the separation after complete debonding occurs at the very end of an in-plane tear test. It is noted then that the sheet once debonded offers little further resistance to completion of the separation.

Using tweezers, single fibers or groups of fibers can be pulled from the edge of the sheet. Considerable force and, presumably, considerable work is needed to dislodge the fiber from the structure by the breaking of bonds. Once the fiber has been debonded, however, one has no feeling at all of a resistance being offered to further extraction. Obviously, this is a most difficult subjective observation to make. There is certainly some force involved in the further extraction of the fiber from the structure and one probably cannot detect, or subjectively evaluate, the small forces. The observation that the debonding zone increases slightly upon further separation of the two torn portions suggests that the growth in the debonding zone is due probably to the very long fibers. These fibers are of interest since they could be debonded and extracted from a relatively intact sheet structure and the concept of fiber friction would appear to be relevant in this part of the in-plane tearing process. However, the question of whether the work done to remove these fibers from the sheet is found principally in the extension of the fibers during the bond-breaking period or whether there is significant work involved in removing the fiber from the surrounding structure after the fiber-fiber bonds have been broken cannot be resolved by subjective evaluation.

A complication is found in the question of whether a fiber can be stressed repeatedly to various stress levels followed by the rupture of one or more bonds, with a loss of some strain energy, whereupon further extension is resisted by other bonds, again developing stresses in the fiber, followed in turn by bond breakage, further loss of energy, etc. Such a process could, of course, magnify greatly the energy contribution assessed to an individual fiber. One certainly can imagine this situation occurring in the tearing of paper where fibers which had been stressed once to become partially debonded are stressed again to effect further debonding. It illustrates the kind of complication which makes it exceedingly difficult to account for the energy dissipated in a tearing process in some quantitative sense.

Despite the obvious shortcomings of subjective analyses of the tearing process, it is felt that a large part of the in-plane tearing energy must be energy associated with the process of debonding of the bonded structure either with or without fiber rupture. This energy must be principally involved in the extension or other deformation of fibers or fiber segments.

THE TEARING STRENGTH OF ANISOTROPIC PAPER

Variations in paper properties in the plane of a sheet result from two principal effects. There may exist a preferred orientation of the fibers in the plane of the sheet and/or the sheet may have been subjected to nonuniform stresses in its plane before, during, or after drying. The anisotropic character of the resulting sheet is indicated by differences in tensile modulus, tensile strength, elongation at rupture, etc. It is characteristic of the tearing strength of paper that it is much less sensitive to the anisotropic character of the sheet than are the in-plane tensile properties. For example, in sack kraft papers, the Elmendorf tearing strength of the machine-made sheet may be practically identical whether the tear proceeds in the machine or cross-machine direction despite the anisotropy indicated by the in-plane tensile properties. Obviously, any analysis of the tearing strength property of paper must deal successfully with this situation.

Some typical ratios of tensile strength, single-sheet Elmendorf tearing strength and in-plane tearing strength are presented in Table III. These data are taken from the work of Van den Akker, et al. (14). Despite the limited data, the reader will note that, with the exception of the extensible kraft bag paper, the Elmendorf and in-plane tearing strength ratios are surprisingly similar and both are nonlinearly related to the tensile strength ratio.

Prusas (16) was able to vary fiber orientation in a laboratory sheet mold and noted that fiber orientation had a much smaller effect on the Elmendorf tearing strength ratio than on the tensile strength ratio. From equations presented by Prusas, at the maximum fiber orientation which he could obtain with a hardwood NSSC pulp, a tensile strength ratio of 2.14 was noted compared to a tearing strength ratio of 1.43.

TABLE III

TENSILE AND TEARING STRENGTH RATIOS FOR SEVERAL MACHINE-MADE PAPERS

	M.D./C.D. Tensile Strength Ratio	C.D./M.D. Elmendorf Tear Ratio[a]	C.D./M.C. Elmendorf Tear Ratio[b]
Newsprint	2.70	1.79	1.59
Kraft liner	2.58	1.41	1.46
Rag bond	2.08	0.95	1.11
Kraft bag	1.62	1.15	1.02
Extensible kraft bag	1.07	1.07	1.36

[a] Determined by tearing single sheets.

[b] Determined at 8.1° included angle.

No data could be found in which tearing strength anisotropy was studied as a direct effect of nonuniform restraints applied during drying of the sheet. It might be assumed that, by permitting a sheet to shrink during drying as opposed to restrained drying, the tearing strength would be increased because of an increase in the work of extension of the individual fibers within the sheet. Of course, other effects would also be present. Schmidt and Henderson (17) reported, in one instance, that the Elmendorf tearing strength increased by about 30% when a handsheet was permitted to shrink freely (4.9% shrinkage) compared to the standard TAPPI handsheet (0.7% shrinkage). It should be noted that, along with an increased tearing strength of about 30%, the stretch increased by a factor of more than two.

Giertz and Helle (18) observed that the Elmendorf tearing strength of a birch sulfite pulp increased by about 33% when handsheets were allowed to shrink freely compared with drying on plates. When 20% of cotton was added to the furnish, the tearing strength increased by a factor of two, yet the absolute increase in tearing energy observed for free shrinkage of these sheets was no greater than that obtained for the original pulp.

It is of interest to consider the work required to break a wood pulp fiber as a function of the axial restraint applied to the fiber during drying. Jentzen (19) noted that the work-to-rupture increased about 30% for longleaf pine summerwood fibers dried under load compared to drying under no load. This was probably near the maximum increase possible. For springwood fibers, an increase of 40% was noted in the work-to-rupture and it appeared that this too is near the maximum possible value. Spiegelberg (20) observed that the work-to-rupture increased with the first increments of drying load used in the drying of individual fibers but decreased thereafter to values approaching, in some cases, the work-to-rupture of fibers dried without load. From these studies of the properties of the individual fibers, one can, at least, expect a circumstance where elastic modulus, tensile strength, and extension at rupture could be changed by factors of two or more through changes in the restraints applied during drying but without significant changes in the work required to rupture the fiber. If a change in the fiber rupture work did occur, it would likely be in the direction of increasing work with increasing restraint. This, of course, is opposite in direction to an increase in tearing energy with increasing shrinkage. The paradox lies in the fact that the forces applied to the fibers are limited in magnitude by the strengths of the bonds. The energy involved in fiber extension to a given stress value could be considerably greater for fibers which have been permitted to shrink compared to those which have been dried under restraint. If, on the other hand, the bonding were adequate to produce a very high percentage of fiber ruptures, relatively little difference might be expected in tearing strength because of differences in fiber extensibility.

It seems rather obvious from the foregoing discussion that it would be difficult to predict from the work involved in the extension of the individual fibers some reasonable values of the tearing strength ratio even if this were the only energy dissipative process involved.

Another situation which should be considered in discussing tearing strength anisotropy is the possibility that, whatever the energy dissipative processes, fibers lying at all angles to the tearing direction contribute significantly to the total energy of the tearing process. Thus, in this sense, tearing would be considered more nearly biaxial than uniaxial in the distribution of stresses throughout the zone of fracture and the immediate vicinity. While there is some rather scattered evidence which might tend to support the view of biaxial stressing during tearing, no good case could be developed either for or against the concept.

STRETCH-TEARING ENERGY RELATIONSHIPS

It appears to be rather generally accepted that increasing stretch could be expected to correlate with increasing energy involved in the tearing fracture of a sheet, despite a general inability to establish such a stretch-tear relationship in the usual experimental studies involving beating and wet pressing as principal variables. The difficulty probably lies in the fact that the extension of a specimen at the moment of tensile failure may bear no particular relationship to the strain of the individual fibers or fiber segments in the fracture zone during the tearing process.

If it were assumed that the in-plane tearing energy was largely related to the work of extension of the individual fibers and fiber segments in and near the fracture zone, one would expect to be able to establish a relationship between the extensibility of the fibers and the energy required in the tearing fracture of the sheet. Some very obvious complicating factors make it difficult to seek relationships of this kind experimentally. Perhaps the most interesting approach is one of testing sheets at different moisture contents. If only the moisture content of a sheet is changed, the principal structural features of the sheet should remain largely unchanged. For example, the relative bonded area should be approximately the same at the various relative humidities. The number of bonds per unit of fiber length, the distribution and dimensions of the unbonded fiber segment lengths will also remain essentially the same as will the fiber length distribution, etc. Data of this type are not available for the in-plane tearing strength of paper, but data have been published of the Elmendorf tearing strength at different relative humidities. Perhaps the best data of this type are that of McKee and Whitsitt (21) in which two samples of regular sack kraft and two samples of extensible sack kraft were tested at relative humidities of 10, 25, 50, 70, and 85% R.H. It was felt worthwhile to reproduce these data in Table IV.

The M.D. and C.D. Elmendorf tearing strengths are quite similar and are affected rather similarly by changes in relative humidity. It appears that the energy involved in the tearing fracture of these papers could be a biaxial property if stretch were considered to be related to tearing energy. Either the machine or cross-machine direction Elmendorf tearing strength is better related to the sum of the two stretch values than with either directional stretch value. A plot of the average Elmendorf tearing energy *versus* the average stretch values (Fig. 7) shows that, although the relationship is not strictly linear, as a first approximation, the tearing energy is proportional to the average stretch. Further, the crude extrapolation of the curves is toward the origin, suggesting an absence of tearing energy in the absence of sheet extension before rupture. When one considers the complicated nature of the Elmendorf tearing process plus the rather poor understanding of the factors which determine elongation at the tensile rupture point, one should

TABLE IV

PHYSICAL PROPERTIES OF KRAFT SACK PAPERS AT DIFFERENT RELATIVE HUMIDITIES

(McKee and Whitsitt) (21)

	R.H., %	RK-1	RK-2	EK-1	EK-2
Basis weight, (at 50% R.H.)		83.5	81.6	83.8	87.3
Tensile strength, M.D., lb./in.	10	37.9	37.3	20.6	20.3
	25	38.4	37.6	21.0	20.9
	50	34.4	33.8	21.0	20.2
	70	31.5	30.0	19.3	19.4
	85	25.0	25.3	17.3	17.1
Tensile strength, C.D., lb./in.	10	22.9	23.3	21.3	21.9
	25	22.6	22.5	20.6	21.5
	50	20.9	20.8	19.1	20.4
	70	19.0	18.5	17.1	18.2
	85	15.4	15.2	15.0	15.4
Stretch, % M.D.	10	1.1	1.2	5.0	7.1
	20	1.2	1.2	6.2	8.6
	50	1.3	1.5	8.7	11.3
	70	1.6	1.8	9.9	12.5
	85	1.8	2.0	10.5	13.3
Stretch, % C.D.	10	1.9	2.0	2.2	2.1
	25	2.4	2.4	2.7	2.7
	50	3.5	3.5	4.4	4.3
	70	4.4	4.2	5.5	5.3
	85	4.9	5.2	6.3	6.0
Elmendorf tear, M.D., g.-cm./cm.	10	156	144	148	160
	25	188	174	184	204
	50	236	218	242	264
	70	294	260	298	328
	85	356	312	366	396
Elmendorf tear, C.D., g.-cm./cm.	10	174	164	158	184
	25	202	198	202	238
	50	246	242	262	302
	70	296	274	324	374
	85	356	330	376	422

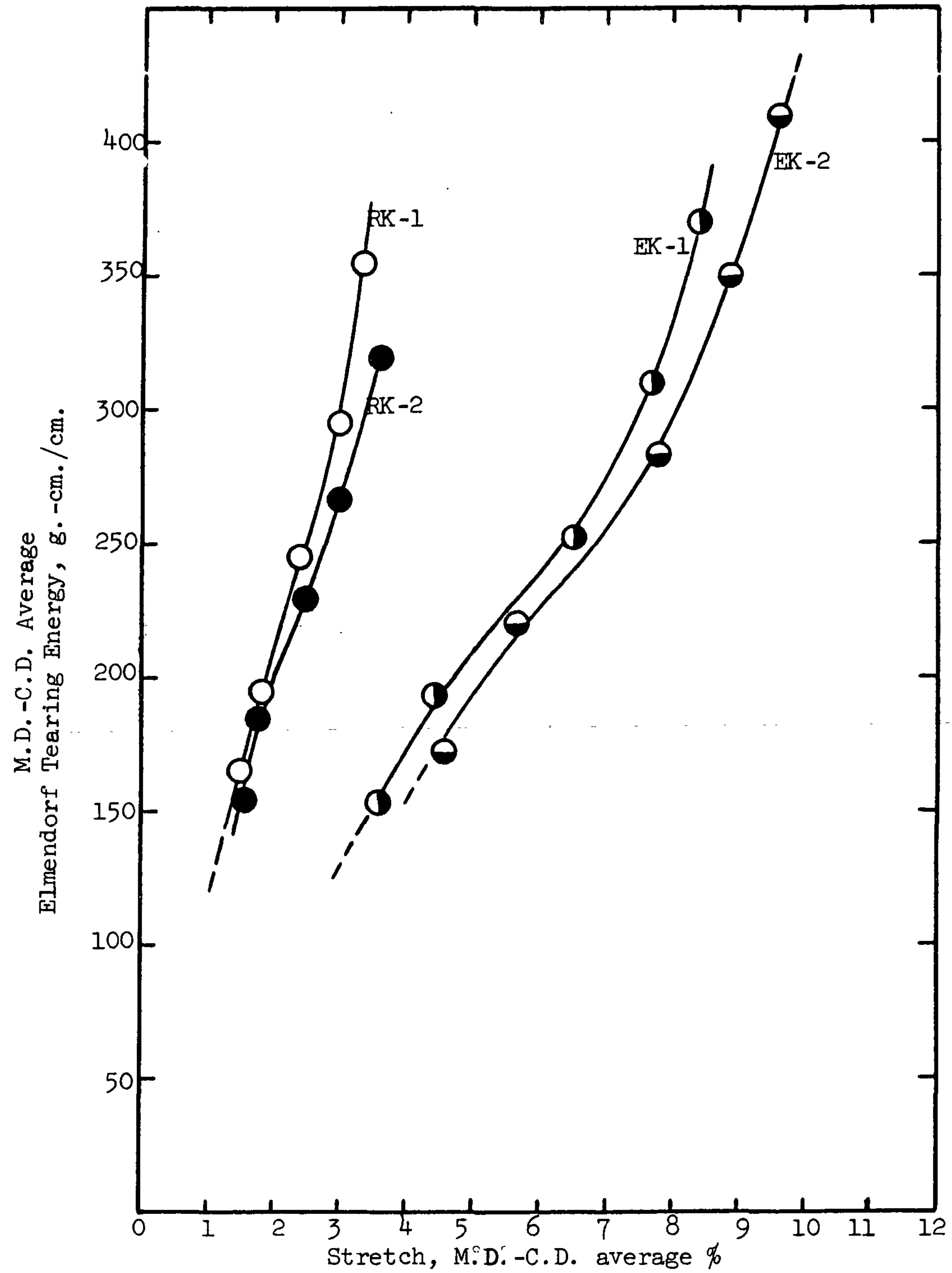


Figure 7. Tearing Energy Versus Stretch Relationships for Machine-Made Kraft Sack Papers Tested at Different Relative Humidities

be cautious in interpreting any relationship between stretch and Elmendorf tearing energy. A reasonable conclusion, at present, is simply that stretch and the energy of tearing fracture might both be increased by increasing extensibility of the individual fibers as a result of increasing relative humidity.

In the case of these Elmendorf tearing data, it can be expected that if a reduction in bonding strength occurs at the higher relative humidities this would result in increased tearing strength. It would be interesting to have similar data for the in-plane tearing strength where the reduction in bonding strength could be expected to reduce tearing strength rather than to increase it. Despite this complication, it is felt that these data do illustrate an effect of increasing fiber extensibility on tearing energy. It is equally obvious, however, that the stretch of the sheet cannot be related to tearing strength in any general sense. The very high M.D. stretch values for the extensible kraft papers are unfortunately associated with rather low M.D. tensile strengths which prohibit any meaningful conclusion about the high stretch without a higher tearing strength.

The behavior of a sheet up to the instant of tensile rupture is not a good measure of the deformation which may be suffered by fibers in the tearing fracture zone. It is most likely that the extension of fibers in the tearing zone will easily exceed the fiber extension in a sheet tensile test and that far more energy could be involved in the extension of fibers in the tearing fracture zone than would be predicted from the tensile energy absorption up to the point of sheet tensile rupture.

ESTIMATES OF FIBER LOAD-DEFORMATION ENERGY IN TEARING

Some portion of the energy dissipated in the tearing process must be due to work involved in the deformation of individual fibers and fiber segments. The fact that many fibers are stressed to the point of rupture is evidence that substantial forces exist in the fibers in the tearing zone even in relatively weak sheets. If appreciable percentages of fibers are ruptured, it is possible that those which did not break may still have been stressed to levels near the fracture point with an appreciable expenditure of energy. Data available within the past few years make it possible to estimate the work involved in the axial extension of fibers. There are no data at all, however, about the amount of fibrous material involved in the tearing fracture. If an individual fiber is loaded to rupture in axial tension, the fiber would have been gripped at two reasonably well-defined points and it is the substance between the gripping positions which is strained and associated with the work done in the tensile straining process. If the initial test span is increased, more work is done because a greater amount of fiber is involved. However, in the tearing zone, one simply does not know what forces exist in what fibers over what fiber length dimensions. Most likely the forces vary from segment to segment reaching maximum values within a primary fracture zone and with lesser values away from this area of concentration of stress.

Little can be said about the extension of fibers which lie almost in the direction of tear. It seems reasonable that such fibers cannot be stressed as highly in the axial direction as fibers which lie directly across the tear line. Most of the ruptured fibers do appear to lie essentially across the tear line, although fibers which lie practically parallel to the tearing direction have been broken in an in-plane tearing fracture. It seems best to assume that some work is done on fibers lying at all angles to the tear line with maximum values for fibers across the line of tear. It is impossible to estimate the load-extension work by summing the exact contributions of all pertinent fibrous elements. It is, however, possible to make an order-of-magnitude estimate of the work which could be associated with the axial extension of fibers to a particular level of stress within a prescribed area of the sheet.

The classified softwood bleached sulfite pulp used in this study had an average fiber length of about 1.4 mm. at the 5-min. refining interval. An average tensile strength for the individual fibers of this pulp would be in the order of 100 kg./mm.^{2} based on computed cross-sectional areas assuming the fiber density to be 1.55 g./cm.^{3}. Less data are available regarding the average elongation of fibers at rupture. Apparently, the "stretch" of individual fibers varies considerably and depends highly on restraints applied during drying. An average elongation at rupture of 5% is a reasonable estimate for this pulp. The shape of the load-elongation curve, of course, is involved in determining the work of extension. A good general first approximation is that the load-elongation curve is linear over its entire length, which facilitates calculation of the work involved in the extension of the fiber per unit weight of fiber. Based on the values given above, the work-to-rupture is determined to be about 160,000 g.cm. per gram of fiber. This value is in good agreement with the work-to-rupture values determined by Spiegelberg (20).

The uncertainty of knowing the amount of fibrous material which could be stressed to any assumed level of stress makes it necessary to select some arbitrary value. If it were assumed that all of the stressed fiber were located within a zone defined by the length of the tear (1 cm.) and the average fiber length (0.14 cm.), a sheet area of 0.14 cm.^{2} would be involved per cm. of tearing length. At a basis weight of 60 g./m.^{2}, the weight of fiber within this area would be about 8.4×10^{-4} g. For this amount of fiber, the load-elongation work would then be 134 g.cm. per centimeter of tearing length, which is greater than the expected maximum in-plane tearing energy for this pulp (about 110 g.-cm./cm.). Actual in-plane tearing energies of 67.5 and 86.2 g.cm./cm. were measured for the 5 and 20-min. refining intervals, respectively. In earlier work on this project, an in-plane tearing energy of about 100 g.cm./cm. was obtained for the same pulp at the 40-min. refining interval.

If the stress in all fibers within this rupture zone reached the level of the average tensile stress, perhaps about half of the fibers would be broken. This is a reasonable fiber rupture frequency at the maximum in-plane tear point. The probability that the stresses in fibers lying in the direction of the tearing line may be appreciably lower than the assumed stress level could be compensated by the likelihood of the area of significantly stressed sheet being greater than the assumed area. Little more can be gained at this point by further speculation about the stresses experienced by the various fibers and fiber segments in the tearing of paper. Calculations of this type suggest that the work of extending fibers could account for much of the energy expended in the in-plane tearing of paper. For this test, it may not be necessary to seek significant contributions to the total tearing energy in other energy dissipative mechanisms. Calculations for other pulps yielded similar estimates of the work of fiber extension relative to the maximum in-plane tearing energy.

THE CONCENTRATION OF STRESS IN TEARING

As long ago as 1932, Clark (22) expressed the view that tearing strength depended on the "degree of localization of the applied stress." He illustrated the point by relating the low tearing strength of cellophane to tearing forces which are localized within a very narrow zone and the higher tearing strength of paper to tearing forces which are more broadly distributed. The general concept that through greater concentration of stress less energy may be required for rupture of a material is rather straightforward. It is based on the view that the critical stress which must be reached before a material will break must be developed by forces transmitted to the rupture area through the specimen and that the work done in the rupture process is due mainly to the stretching of the specimen. Thus, more work will be done when large stresses exist over a large volume of specimen and less work is involved when the stresses are concentrated close to the fracture zone. The key thought here is that the work has to be largely involved in the deformation of the specimen. It is rather easy to visualize this in the tearing of solid films.

In the tearing of paper, there is concern about the amount of fibrous material which is stressed, the distribution of these stresses, and the work which might be associated with deformation of the fibrous material. It seems certain, however, that the effect of stress concentration on the work of tearing as visualized for films cannot be applied directly to the tearing of paper.

Consider the in-plane tearing of a bonded fiber network (paper) in which fibers are not ruptured. Separation of the specimen into two portions would first require the breaking of some minimum number of fiber-fiber bonds. The minimum number of bonds which must be broken in different papers should be roughly proportional to the fiber length, and, if all other factors were constant, the work required to do this might also be proportional to fiber length. With increased numbers of bonds, area of bonds, or strength of bonds, it can be assumed that the stresses in the fibers will increase, thereby increasing the deformation and the work of the deformation process. This would indicate that the fiber deformation work term would increase steadily with increasing sheet strength. As appreciable numbers of fibers are ruptured in stronger sheets, fewer fiber-fiber bonds need be broken. The bonds may remain unbroken simply because they are strong enough now to resist forces of similar magnitude; however, it is also possible that forces would be lower generally at the periphery of the fracture zone as a result of fiber rupture. If this does happen it represents a greater concentration of stress and might act to reduce the work required to tear paper. It must also be considered that as more fibers are ruptured the level of the stress continues to increase and this increases the energy of fiber deformation. It seems probable that quite a high percentage of fiber fractures would be required before the load-deformation energy contribution to the tearing work could be reduced through a mechanism of stress concentration.

Giertz and Helle (18) pointed out that, even when the degree of refining was extensive and fiber breakage was high, the Elmendorf tearing strength still seemed to be related to fiber length. He felt, apparently, that, with a high degree of fiber rupture, the fiber length effect should be reduced and perhaps eventually disappear as a factor affecting tearing strength. Giertz added 20% of viscose rayon fiber of 10-mm. length to a sheet and noted that, although most of these fibers were broken during tearing, the Elmendorf tear factor improved by about 50%. He attributed this added energy to stretching of the sheet outside the tearing fracture zone. In effect, Giertz intimates that stresses are distributed over a wider area because of the long viscose fibers. It might, however, be possible to account for much of the increased energy directly in terms of the work required to break viscose fibers. Unfortunately, in order to calculate the work to rupture, knowledge of the distribution of stress along the fiber is needed.

The foregoing discussions of the tearing property of paper were aimed at developing a better understanding of the possible relationships between tearing energy and the work involved in the straining of fibers and fiber segments in the tearing fracture zone. In analyzing the tearing process, it was felt that the work of deforming the fibers may be the principal energy dissipative mechanism of the primary fracture process which results in the breaking of fiber-fiber bonds and in the fracture of fibers. It is possible that in the in-plane tearing of paper no other significant energy dissipative mechanism is needed to account for the observed tearing energy. The greater tearing energy measured by the Elmendorf method, particularly with the more poorly bonded sheets, might be related to an increase in the amount of fibrous material which is strained, to differences in the nature of the fracture, and/or to significant contributions from other energy dissipative mechanisms such as fiber-fiber friction. It should be evident to the reader that the present understanding of the tearing process is not yet good enough to justify quantitative tearing energy analyses based on simple factors such as the frequency of fiber rupture.

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